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Lightweight Arm Operations for Planetary Sample Return

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Abstract

The Beagle 2 robotic arm was studied to evaluate its suitability as a basis for the design of a lightweight instrument deployment arm for a future planetary rover mission. Newly developed circuitry allowed the arm to be driven in ways it had not been used previously. In particular, joint interpolated motion for straight-line trajectories was demonstrated. The repeatability of instrument positioning was found to be within 0.5 mm. Angular positioning of instruments was subject to larger errors (up to 4.5°), mainly due to known issues with bevel gears on the last two joints. This can easily be remedied without extensive re-design, making the arm highly suitable for a rover mission. In order to take full advantage of the capabilities of the arm, a calibrated physical deflection model will be required to replace the current kinematics model.

1 Introduction

The Aberystwyth University (AU) Space Robotics Research Group has undertaken a study, funded by the European Space Agency within the ExoMars project, evaluating the use of a lightweight robotic arm for a future planetary rover mission. This work began as a Phase B1 study into the key instrument deployment requirements for an Instrument Deployment Arm (IDA) for the ESA ExoMars rover vehicle. ExoMars is the first of the Aurora Exploration missions funded by the European Space Agency, with Thales Alenia Space Italy as the Prime Contractor. As part of this study we have developed a control strategy allowing the arm to move with near-straight line motion for relatively little computational cost. This is a key enabling requirement for autonomous precise instrument positioning and imaging work.

The requirements specified the IDA's working envelope, positional and angular repeatability and accuracy, instrument positioning and re-positioning, and its ability to deploy an instrument without requiring a further iteration cycle from ground control. Due to the recent review and restructuring of ExoMars as part of a joint NASA/ESA mission (now scheduled to launch in 2018), the IDA itself will not now be included as part of the ExoMars rover vehicle. However, the use of a robotic arm with contact instruments and a manipulator will be crucial to the success of any future mission to select and retrieve samples from a planetary surface – in particular, the proposed Mars Sample Return (MSR) mission.

2 Key ExoMars IDA requirements

The following is an abridged list of key requirements for the ExoMars Instrument Deployment Arm that were addressed in this study.

1. Deployment of selected instruments and tools shall be possible on all target positions within a 90° full cone at a distance between 15 and 50 cm from the Rover. The approach direction at the target positions shall range from vertically downwards to horizontal.
2. Target points situated at least 5 cm below the ground plane flat terrain shall be reachable with all close-up instruments.
3. It shall be possible to position the reference point of a deployed instrument in a single operation, with a position accuracy of 1 cm (radius of a sphere) and an approach direction accuracy of 0.5° half cone angle.
4. It shall be possible to reposition the reference point of another instrument with respect to the reference point of the current instrument with an accuracy of 0.5 mm (radius of a sphere) and 0.1° half cone angle.

(These requirements were abstracted from ESA document reference EXM-RM-SSS-AI-0014)

3 Arm hardware

The preliminary baseline design for the IDA considered in the study was the Beagle 2 (B2) arm. This is a relatively lightweight and compact folding 5-DoF arm design, which would be well-suited to deployment on a mobile platform. The AU study has made extensive use of the B2 Development Model (DM) arm [1,2] on loan from EADS Astrium, which is the twin of the one sent to Mars as part of the ESA Mars Express/Beagle 2 mission in 2003. The arm as flown carried a multi-instrument head, the Payload Adjustable Workbench (PAW) which held a number of instruments and cameras. For the purposes of ground-based testing and calibration during the Beagle 2 mission, a one-third mass copy of the PAW was created using rapid prototyping methods. This was used in this study to simulate the arm mass loading of the real PAW on Mars.

Each of the five arm joints has a motor and gear assembly and a potentiometer for directly measuring the joint angle. There are no shaft encoders or other speed sensors. Constraints imposed by the very limited space available for the stowed arm and PAW, together with the requirements for placement of the PAW instruments during operations resulted in a design with right-angle bevel gear joints between the arm and wrist (last link of the arm) and between the wrist and the PAW. The backlash inherent in these gears proved to be a significant source of positioning error in this study.

4 Test environment

All testing and measurement as part of this study took place in the AU Planetary Analogue Terrain Laboratory (PATLab) [3]. This laboratory houses a 50 m^2 simulated Martian terrain with Mars Soil Simulant-D and a selection of geologically-characterised target rocks. The PATLab is also equipped with a twelve camera Vicon MX motion tracking system. This system uses specialised infra-red cameras to track the position and orientation of multiple objects defined by reflective markers, in real time, at frame rates of up to 120 fps. The positional measurement accuracy of the Vicon system in three dimensions is sub-millimetre when well-calibrated. This system was used to take ground truth measurements of arm position and attitude throughout the study.

4.1 Physical test rig

A test rig was built (Figure 1) that emulates the base and front sections of a rover vehicle, and this was raised to the proposed ExoMars rover base height above nominal ground level. The B2 DM arm was mounted on this rig, and dedicated circuitry was built to provide the necessary motor drive interface and individual joint motor speed control. This circuitry also provides an interface to standard computing hardware for arm control input and joint angular feedback purposes.

The arm has two possible mounting positions on the test rig. One configuration has the arm mounted on the horizontal calibration rig plate with the joint 1 rotational axis vertical - the “Beagle 2” mount configuration (Figure 1).

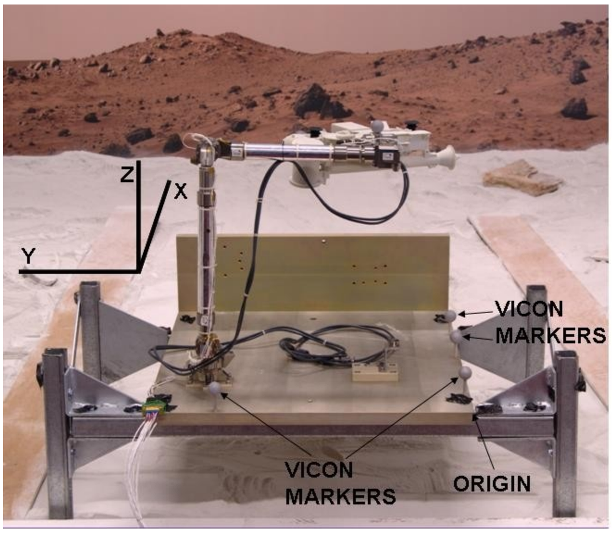

Figure 1. IDA study test rig: Beagle 2 configuration

The alternative configuration has the arm mounted on the front vertical calibration rig plate with the joint 1 rotational axis horizontal - the “ExoMars” mount configuration (Figure 2). Both configurations were used at different times during the study.

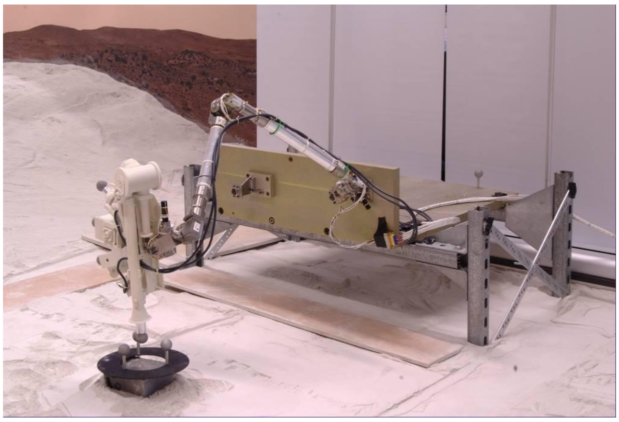

Figure 2. Test rig: ExoMars configuration with instrument arm deployed

The test rig also incorporates reflective markers at precise positions that provide a reference origin and axes for the Vicon tracking system that are locked to the arm. Further reflective markers on the arm and PAW allow precise tracking of position and attitude of the instrument head.

4.2 Simulator environment

In addition to the physical test rig, a virtual workcell environment containing a CAD-based model of the B2 arm was constructed within the Envision robot simulation system. Figure 3 shows the arm model in its virtual workcell, with the five joints of the arm labelled. Also visible is the instrument head (PAW) The model was based on B2 CAD data supplied by EADS Astrium.

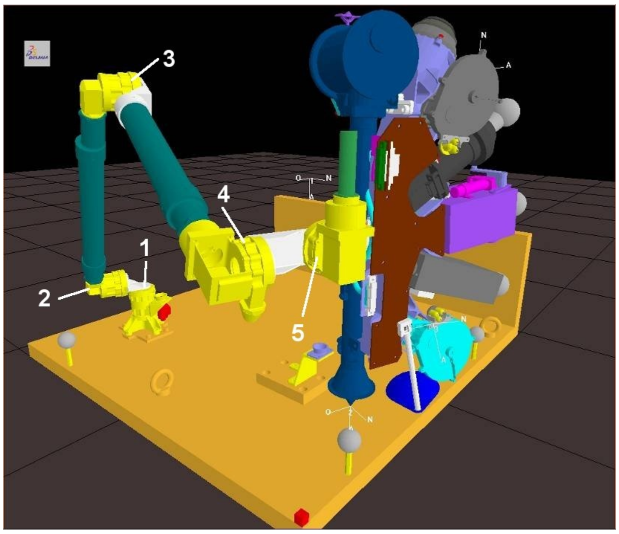

Figure 3. Virtual workcell

The simulator was used to set up experimental scenarios and to compute distances and arm joint angles using an appropriate kinematics model. Calculated joint angles were transferred to the real arm for testing. Virtual workcells were constructed within the simulator corresponding to both of the arm mounting configurations described in section 4.1 .

4.3 PWM speed controller

The B2 DM arm as supplied by EADS Astrium included "H-bridge" power driver circuitry with a parallel interface and a switch box for manual control. Additional hardware and software was designed to allow precision automatic control and measurement of the arm during testing. This included a multi-channel pulse-width modulation (PWM) control board using a dedicated microcontroller (PIC18 series) to ensure reliable waveform generation under software control. The PWM speed controller board has a fast parallel interface and is capable of driving all five arm joint motors simultaneously at different speeds, with a base PWM frequency of 500 Hz. A total of 128 forwards and backwards speed steps are available from the controller, along with a number of configuration commands.

4.4 Control PC and interface

All tests were controlled and monitored by a standard desktop PC running the Linux operating system. An EDRE EagleDAQ PCI730 combined A-D/D-A and digital I/O board provided an interface between the PC, the PWM controller board and the arm joint angle potentiometers and their associated reference voltage source. The board is capable of sampling 16 input voltage channels with 14-bit resolution at up to 100,000 samples/sec as well as providing 3 × 8-bit bidirectional I/O ports, which were used to control the PWM board.

4.5 Arm control software suite

A test suite application allowing both interactive and automatic control and monitoring of all arm parameters was developed for this study. The software implements a command language that supports the definition and execution of movement sequences in different modes (serial, parallel and joint-interpolated), measurement of arm position and pose via the Vicon tracking system and of joint angles via the arm joint potentiometers. The software also supports running from script file input, enabling repeatable and automatic test setup and execution.

5 Arm kinematics study

The study commenced with a repeat of the B2 DM arm positional repeatability and accuracy measurements originally conducted prior to the launch of Beagle 2 and described in detail in [1]. The kinematics and calibration model developed for the B2 arm relies on knowing the position and orientation of the desired target point relative to the Beagle 2 lander body. A different set of calibration parameters are loaded depending on which instrument is in use and in which region it is operating.

Calibration measurements were taken prior to launch for each instrument operating in each of its distinct target regions, according to the requirements of the nominal mission. A total of 10 possible calibration sets were developed for each of the DM and FM (Flight Model) arms, but not every possible combination of instrument and target was included. Re-use of the B2 calibration data for this study required identifying the most appropriate working region for each instrument and target position.

5.1 Positional repeatability

After choosing a specific target point, a set of starting points was defined within the simulator workcell with the arm joints moved away by about 20° in different directions. The trajectories were designed to exercise different motions of each arm joint. The arm was then moved from each starting point to the target position. The final position reached and its associated error was measured in each case.

Results were expressed in terms of the radius of a sphere enclosing the measured goal point final positions and 1sd error bounds from the measurement system. Three separate runs yielded results of: 0.554 mm ±0.058, 0.299 mm ±0.031 and 0.498 mm ±0.027. These figures are consistent with previous measurements of the DM arm during the B2 calibration campaign and slightly outside the ExoMars acceptable margin of 0.5 mm (at least for run 1).

5.2 Positional accuracy

To test the positional accuracy of the arm, joint angles were calculated in the simulator to place one of the PAW instrument tips above a known reference point in the workcell (one of the Vicon markers). In this case, the nearest calibrated region was about 350 mm distant from the instrument tip, which will have affected the positional accuracy.

The measured positional accuracy for this test (Euclidean distance) was 7.515mm ±0.012. Despite the kinematics model not being optimised for this working region, the result is within the required 10 mm radius error sphere for ExoMars.

5.3 Reachability envelope

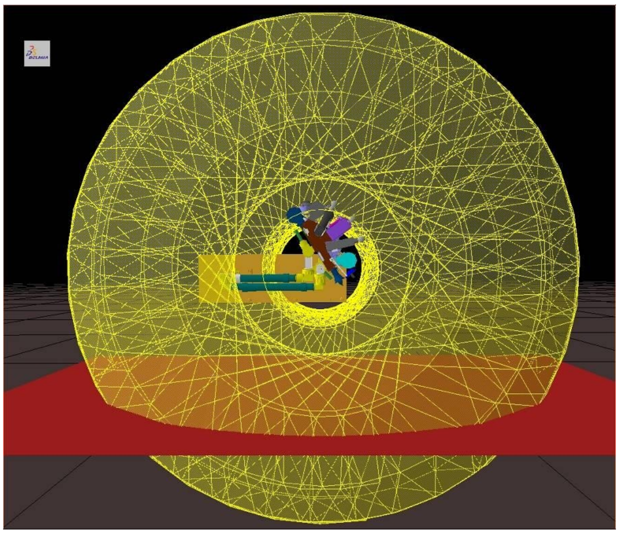

Figure 4. Arm reachability envelope (front)

To visualise and measure the arm work envelope, simulation work was performed using the arm in the vertical (ExoMars) mount configuration. Wire-frame arm envelope objects were generated using the arm kinematics model with a particular PAW instrument (the Mössbauer instrument) as the kinematics end-point. The arm envelope algorithm uses the first three joints of the arm kinematics model together with an additional translation offset to account for the Mössbauer instrument end-point.

The envelope objects generated from this process can be visualised together with the simulated calibration rig and arm and measurements undertaken. What can be seen is the reachability volume of the arm for a given instrument end-point, i.e. the instrument can be placed at any point within this envelope volume.

The current B2 arm design exceeds the baseline ExoMars IDA reachability requirements, though due to the 5-DoF nature of the arm, some combinations of target position and instrument orientation may not be achievable.

6 Trajectory control

During the Beagle 2 mission the arm was to be moved joint-by-joint and employed a bang-bang [4] joint motor control method, i.e. there was no simultaneous multiple joint motion, and no joint motor speed control. This control strategy was appropriate for a static lander mission, but for use on a mobile rover platform such as ExoMars or MSR, more sophisticated arm control methods are required.

The addition of motor speed control to the B2 arm as part of this study has enabled the evaluation of an arm movement algorithm based on joint-interpolated motion, which allows near straight-line manipulator control and instrument placement without repeatedly performing inverse kinematics calculations [5]. A similar approach to arm control has been adopted for the two NASA Mars Exploration Rovers [6].

For this series of tests, straight line trajectories along the X, Y and Z axes were defined within the simulator (Figure 5). The trajectories were divided into shorter line segments bounded by tag or “knot” points [5]. Full inverse kinematics calculations were performed only at these defined points. During the tests, the arm joints were commanded to the angles corresponding to each knot point along the desired trajectory in sequence.

Three variations of arm motion control between the tag points were tested for each trajectory: joint-by-joint, simultaneous full speed (“slew motion”) and joint interpolated.

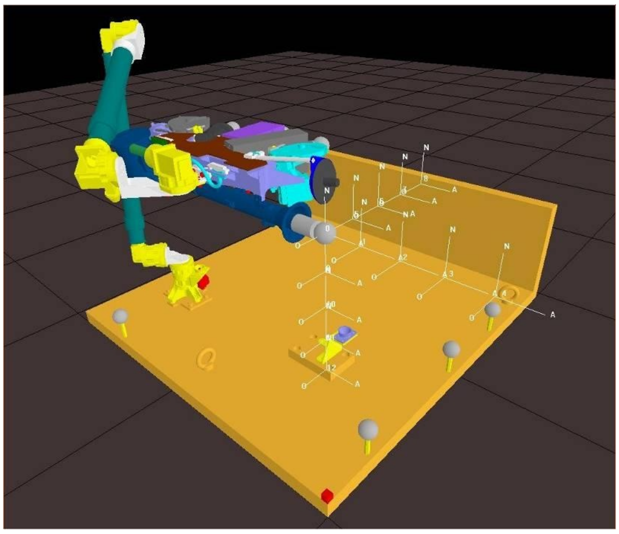

Figure 5. Straight line knot points in x, y and z axes

6.1 Joint by joint motion (JBJ)

In this kind of arm movement, the joints are moved individually in sequence, at full speed. A fixed joint order was used: 5-4-1-3-2. This was the normal mode of operation for Beagle 2. It has the benefit of simplicity of commanding and lower power consumption, as only one motor moves at a time. However, it is slow, and instruments may be swung through large arcs in different planes while moving to their destination.

6.2 Simultaneous full speed motion (SFS or "Slew motion")

With this type of arm movement (commonly called slew motion), all five joints are started simultaneously, at full speed. Each joint is stopped individually when it reaches its target angle. This is considerably faster than joint-by-joint movement. For most arm movements observed it took a more direct route than joint-by-joint, though it was seldom a good approximation to a straight line.

6.3 Joint interpolated motion (JIM)

The theory of joint interpolated motion is that a desired trajectory in *Cartesian space* is approximated by a series of short linear trajectories in *joint angle space* [5]. Provided that intermediate knot points along the trajectory are pre-computed and the arm is moving in a well-calibrated region of its working envelope (and not for example near any singularities), this strategy can result in smoother motion than the other two methods. It does, however, require motor speed control to be available in order for linear motion in joint space to be possible, and this must be calibrated for best results.

The required speed for each joint is determined by first finding the joint that will take the longest time to reach its target angle if moving at maximum speed. The other joint speeds are then adjusted to produce the same total movement time for each joint, so that in theory they will all reach their destinations simultaneously. In practice, motor speed quantisation, stalling, friction and variable deflection and torque forces due to arm position will all contribute to errors in the actual trajectory followed.

6.4 Comparison of SFS and JIM

Figures 6 and 7 compare representative straight-line trajectories for slew motion and joint interpolated motion. These side-view (Y-Z) plots show the trajectory followed and both the commanded and measured knot points for straight-line movement of an instrument head along the Vicon negative Y-direction. The initial large arcs represent movement of the arm from its rest position.

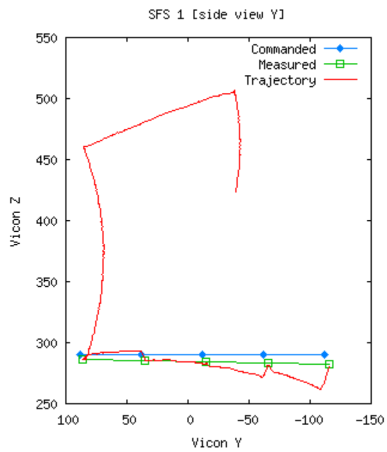

Figure 6. Slew motion trajectory

The smoothness of the trajectory was found to be better for joint-interpolated motion than for slew motion. However, both types of trajectory showed the effect of insufficiently compensated arm deflection at greater extension.

The Beagle 2 kinematics model used for this test was based on the nearest matching calibration region, which only partly fits the actual working area. In addition, the precise effect of arm load on motor speed was not modelled – only an estimate of maximum motor speed was available. The accuracy of arm positioning in general and straight-line motion in particular would be improved by the incorporation of a realistic arm-deflection model into the kinematics calculations.

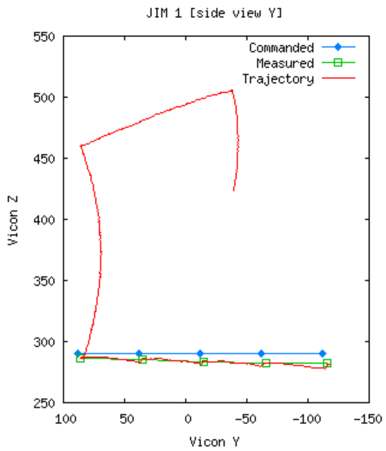

Figure 7. Joint-interpolated motion trajectory

7 Instrument deployment

Three instrument deployment scenarios were tested. One simulated the use of the CLose-Up Imager (CLUPI) instrument, which requires several short, precise movements in order to capture images with different focal planes. The other two were generic instrument deploy-and-swap activities on a single target: one with the arm mounted in the "Beagle 2" configuration, the other in the "ExoMars" configuration.

7.1 Simulated CLUPI deployment

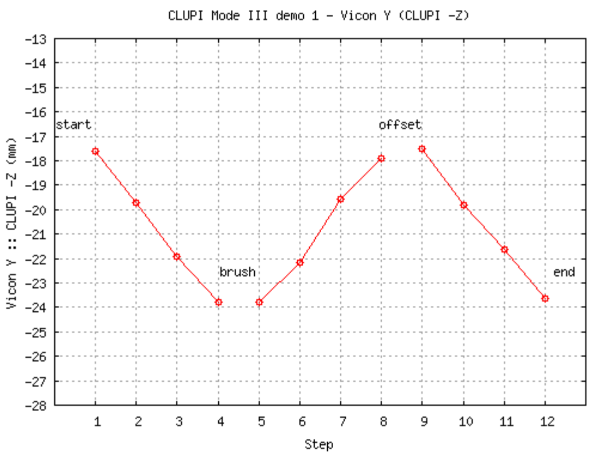

Figure 8. CLUPI deployment (Z-axis)

The simulated CLUPI deployment used the Mössbauer instrument to represent CLUPI and the Mole instrument to represent a "brushing" tool. The CLUPI instrument was advanced in 3 × 2 mm increments, followed by a swap with the brushing tool at the same position. Then the CLUPI position was restored and the instrument retreated in 3 × 2 mm increments. After this, CLUPI was moved sideways by 10 mm and finally the 3 × 2 mm increment advance was repeated (CLUPI "Mode III" operation). Joint angles for the trajectories were calculated using the arm simulator and applied to the real arm using the joint-interpolated motion control strategy. Results from one run are shown in figures 8 & 9. Figure 8 shows good correspondence to the desired accuracy along the CLUPI Z-axis (Vicon Y). The positional increments are close to 2 mm and the repositioning after "brushing" is to within 0.5 mm.

Figure 9 shows the displacement along the CLUPI Y-axis (Vicon X). Clearly the arm is having trouble maintaining an accurate angular instrument yaw (joint 5), whilst performing the 2 mm forwards and reverse. The 10 mm 'sideways' displacement was also less accurate (measured value 14 mm).

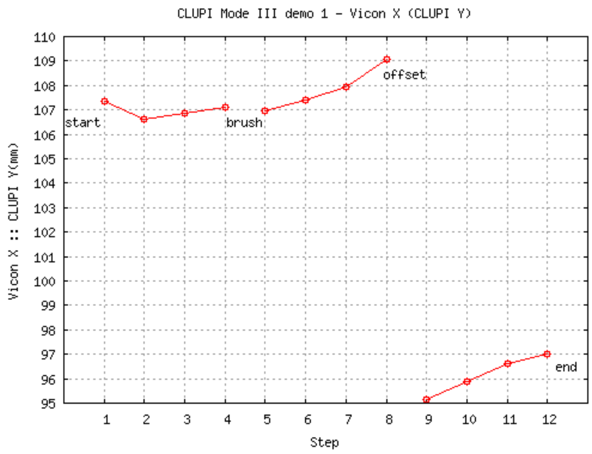

Figure 9. CLUPI deployment (Y-axis)

7.2 Simulated instrument swapping

Three of the PAW instruments in succession were moved along the same straight-line horizontal trajectory. The measured instrument marker positions were used as data for calculating angular repeatability and accuracy values. A further test involved a full arm deployment sequence from the ExoMars stowed position to a pre-determined target, "sampling" of the target in the same place by two different instruments, and re-stowing of the arm. Measurements were taken and a video of this "simulated science operation" was recorded for further study.

7.3 Angular repeatability and accuracy

Angular repeatability was interpreted as a measure of the arm's ability to move multiple instruments in sequence along the same given trajectory (in this case a straight-line trajectory). The relative angular orientation (pitch and yaw) of the different instruments during the simulated instrument swapping exercise was recorded and compared.

Angular accuracy was assessed by measuring the arm's ability to maintain a desired absolute angular orientation (pitch and yaw) for a given instrument when being moved along a commanded trajectory with a specified orientation during the instrument swapping exercise.

The vector between the PAW top Vicon marker and the appropriate instrument tip marker was calculated at three tag points along a straight line trajectory. These vectors were then compared against the ‘as commanded’ vectors derived from the relevant markers modelled within the arm simulator. The experiment was run twice, and the results for each instrument compared.

Results for one run of the two performed are shown in Table 1 (yaw) and Table 2 (pitch), which show the commanded and actual angles for each instrument at the three measurement points along the trajectories. It was found that the best case approach direction angular accuracy was 0.681° (half cone angle: derived from minimum error in pitch for the Mole instrument), and the worst case approach direction angular accuracy was found to be 4.459° (half cone angle: derived from max. variation in pitch for the Rock Corer-Grinder instrument).

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Table 1. Angular accuracy - YAW

Instr	Posn	Comm°	Actual°	Error°
Mole	1	0.467	2.556	2.089
	2	0.466	2.474	2.008
	3	0.466	2.630	2.164
Corer-Grinder	1	5.185	3.858	-1.327
	2	5.182	3.972	-1.210
	3	5.178	4.005	-1.173
Möss-bauer	1	0.583	2.195	1.612
	2	0.583	1.897	1.314
	3	0.583	1.958	1.375

Table 2. Angular accuracy - PITCH

Instr	Posn	Comm°	Actual°	Error°
Mole	1	18.340	19.203	0.863
	2	18.341	19.122	0.781
	3	18.341	19.104	0.763
Corer-Grinder	1	10.381	13.610	3.229
	2	10.343	13.924	3.581
	3	10.286	14.705	4.419
Möss-bauer	1	10.650	13.357	2.707
	2	10.650	13.593	2.943
	3	10.650	13.524	2.874

Errors are seen in both yaw and pitch of the deployed instruments, but for each instrument, the errors are relatively constant. The largest contributor to these errors is thought to be the backlash and play in the PAW joint bevel gears (joints 4 & 5).

8 Discussion and recommendations

The Beagle 2 arm was originally designed for a lander mission in a fixed location. All kinematics calculations were to be performed on Earth, and all arm movements specified in advance at mission control and uplinked as a series of specific commands for execution. The requirements for a rover exploratory mission are considerably more demanding, both in terms of the range of movement required and the variety of trajectories that might be called upon in order to deal with unpredictable aspects of the terrain and mission.

This study has found that the performance of the B2 DM arm has remained consistent with that originally measured, and that it is possible to operate the arm satisfactorily in new ways, such as joint interpolated motion for straight-line trajectory following. The main issues with accuracy concern the distal joints of the arm, which were found to have significant backlash due to the bevel gears used in those joints. This was found to cause errors particularly in the yaw angle of instruments being deployed. This problem could obviously be remedied by re-design of those joints, e.g. by use of harmonic gears as on the other joints (this was not done on Beagle 2 because of mass and space constraints).

A second factor affecting the accuracy of arm placement is the deflection and torsion of the arm links under gravity. This was calibrated out for the static Beagle 2 scenario, but remains an issue for a rover mission. Since the arm is mounted vertically instead of horizontally, unusual loads are placed on the joints, particularly joint 1. Slight re-design of the joints would partly alleviate this (e.g. changing the orientation of joint 1). However, a full solution also requires a more realistic deflection model of the arm to be produced, capable of predicting the magnitude and direction of joint angle correction required to correct any particular arm pose. This would replace the multiple calibration datasets with one parametrised model.

This study has indicated that whilst there is room for improvement to the Beagle 2 arm, there are no serious problems that would preclude its re-use. In many cases only relatively minor improvements would be necessary to equip the arm for the rigours of a future Mars rover mission. Recommendations can be made for further arm development, including the following (a complete list can be found in [7]):

- Simultaneous joint speed control is essential for straight-line trajectory motion. Either motor speed sensors or a calibrated motor speed model should be developed to enable this.

- A combined arm kinematics and deflection model should be developed to support accurate instrument placement and trajectory following in all regions of the arm's working envelope. This would replace the piecewise calibration model originally developed for Beagle 2.
- All backlash in the arm joints should be removed and bevel gears should be avoided wherever possible.
- Arm movement should be controlled by a dedicated arm controller with tight coupling between position feedback and motor control.
- Fiducial markers should be machined on to arm parts to allow key configurations to be accurately checked as part of an overall integrated calibration strategy.

A further development project led by EADS Astrium has been undertaken, which has implemented a number of engineering recommendations and also made improvements to the mechanical design of the arm and its sensor suite. This work will be reported in the future literature.

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